Parameterization of Air-Sea Fluxes for High Wind Conditions

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LONG-TERM GOALS

Improved understanding of fundamental processes of turbulence and air-sea interactions.

OBJECTIVES

The standard model for dealing with turbulence and air-sea interactions has three components:

(1) The ocean surface can be characterized by its temperature and aerodynamic roughness.

(2) Given (1) we can use the wind speed and air temperature/humidity to determine the air sea fluxes. All relevant properties of the profiles of the mean and turbulent fields in the surface layer can them be computed with scaling parameters derived from these fluxes using Monin Obukhov Similarity (MOS) theory.

(3) The small-scale properties of the turbulence (structure functions and inertial subrange spectra) can be described solely in terms of the wave number/spatial separation and the dissipation rate and these are scaled by MOS.

Our objective is to investigate various physical processes that lead either to improvements in the

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representation of the standard model or to violations of the standard model and to develop new models that more thoroughly describe turbulent processes in the marine surface layer. For example, (1) is violated by sea spray, oceanic near-surface mixing processes, and interactions of the wind/stress vectors with the 2-dimensional ocean surface wave spectrum; (2) is violated by near the surface by interactions with waves and is violated far from the surface by intermittent processes associated with larger scale boundary layer dynamics and coherent structures

APPROACH

In this project we focus on three aspects of the problem that are ripe for significant advancement with existing data and model resources: (1) parameterization of the effects of sea spray, (2) examination of the parameterization of surface roughness lengths with wind speed for winds greater than 10 m/s, and (3) realistic representation of subgrid-scale (intermittent) processes in numerical models. The first two issues are primarily relevant to improving parameterizations in high wind speeds. We feel that the field programs of the 80's and 90's have greatly reduced the uncertainty of the representation of fluxes at low and moderate wind speeds and that these results are slowly finding their way into operational weather forecast and climate/GCM models. For example, the recent study by Zeng (1997) found that two operational (ECMWF and NCEP) and two community climate models (CCM3 and GEOS DAS) have flux parameterizations that agree fairly closely for low and moderate wind speeds but begin to diverge wildly for wind speed greater than 10 m/s. The last issue is primarily relevant to the transitioning of experimental results to improvements in numerical models (i.e., 1-hr point measurements of flux versus the average flux over a 100 km square region of ocean).

A specification of roughness length, z_o, is required to relate wind speed to surface stress. This may be done indirectly by parameterizing drag coefficient in terms of wind speed or by using a Charnock relationship which describes the average drag effect of the spectrum of surface gravity waves

$$z_o = \text{"}\, u_*^2/g + 0.11 < /u_* \qquad (1)$$

where " is Charnock's constant, < the kinematic viscosity of air, u_* the friction velocity, and the second term accounts for the transition to smooth flow at low wind speeds. Scalar fluxes (sensible and latent heat) are represented through parameterizations of the scalar roughness lengths (z_{ot} and z_{oq}). Garratt (1992) reviewed the literature on this subject and offers a table with 8 different experimental values of " ranging from 0.01 to 0.035. Numerous attempts have been made to relate " to some simple characterization of the surface wave field (e.g., wave age) but so far these have generally been failures. The COARE 2.5 algorithm uses a Charnock constant of 0.011 which agrees well with several recent sets of ETL open ocean measurements for wind speeds less than 10 m/s. However, we can have seen hints that " begins to increase as wind speed exceeds 10 m/s. This has also been observed by the Southampton groups (Yelland and Taylor 1996) whose extensive measurements (using the inertial-dissipation method) in the strong wind region of the Southern Ocean indicate " increases from 0.011 to 0.017 as wind speed goes from 10 to 25 m/s. Note that " affects both momentum and scalar (heat and moisture) transfer coefficients. Verification of this increase with direct covariance measurements is critical to extending the

COARE algorithm to wind speeds greater than 10 m/s. At this writing, the ETL measurements in the FASTEX (Persson et al. 1997) field program in the N. Atlantic in the winter of 1997 are the only source of direct measurements at these wind speeds.

The two major issues that must be resolved to develop a simple but accurate parameterization of sea spray effects are: (1) a characterization of the oceanic droplet source strength as a function of wind speed (i.e., how many droplets of each size are produced by the various sea spray mechanisms and the characteristic height of their introduction) and (2) a characterization of the *feedback effects* in reducing the total droplet contribution. The first issue can only be resolved by direct measurements of droplet spectra and evaporation rates over the open ocean; the second can be attacked with a suitable numerical model. We are aware of only three field programs with simultaneous measurements of meteorology and atmospheric concentrations of droplets into the large sizes that are relevant to the sea spray problem: the 1987 HEXOS program (de Leeuw 1990), the 1989 UMIST cruise (Smith unpublished), and the 1996 FASTEX cruise (Persson et al. 1997). Because these are only measurements of droplet concentrations (instead of droplet *fluxes*), an evaporation/turbulent transport model is required to deduce the surface droplet source strength. Thus, a model is required for both aspects of the sea spray problem.

Several models have been developed in recent years to investigate droplet effects, however only the new model of Kepert et al. (1998) is sufficiently comprehensive to investigate feedback effects in a physically realistic fashion. This model has an upper boundary at 3 km and uses a full order 1.5, level 2.25 closure scheme for MBL turbulence. If we picture sea spray droplets being continuously thrown into the atmospheric surface layer, then their thermodynamic effect is a battle between their evaporation rate and their atmospheric suspension lifetime (i.e., how much water vapor do they transfer to the air before re-impacting the ocean). The suspension lifetime is a battle between the substantial fall velocity of large droplets and vertical transport by turbulence (which becomes more effective as wind speeds increase). However, the full evaporation of droplets is controlled by the sources of heat available to power the evaporation process and interactions between droplets of different sizes. In dynamic equilibrium, there are only two sources: (1) upward turbulent transfer by sensible heat from the ocean, and (2) downward turbulent transfer of heat from the MBL above the droplet layer. Because evaporation of droplets cools and moistens the MBL and the surface layer, these heat sources adjust internally until some equilibrium is approached. This feedback limits the amount of evaporation produced regardless of the numbers of droplets ejected by the ocean. Thus, this problem cannot be investigated without realistic incorporation of full MBL-scale physics.

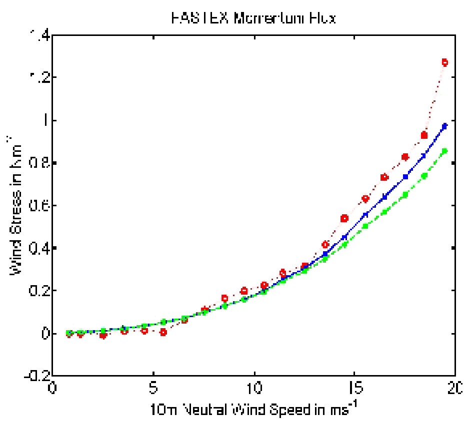
WORK COMPLETED AND RESULTS

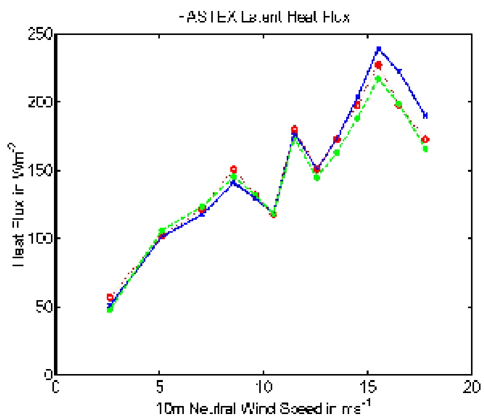
Most of the work done in the last year has been focused on further processing the flux data from the FASTEX experiment and associated improvements in the COARE bulk flux model. The FASTEX work focused on sensible and latent heat fluxes and processing of the wave time series for useful statistics (wave height, period, spectra). Based on FASTEX data and various other sources of information, we have instituted seven changes to the algorithm:

1. The empirical constants in the convective portion of the profile functions have been changed for

improved matching to direct profile observations (Grachev et al., 1999).
2. The Kansas stable profile functions have been replaced by those from Beljaars and Holtslag (1991) based on new profile data taken over the Arctic ice cap.
3. A fixed value of the Charnock parameter ("=0.011) has been replaced by a formulation with a simple wind-speed dependence above 12 m/s based on data from Yelland and Taylor (1996) and Hare et al. (1999).
4. The LKB scalar roughness relationship has been replaced with a much simpler one that fits both the COARE and HEXMAX data bases.
5. The stability iteration loop has been reduced from 20 to 3 using bulk Richardson number parameterization for an improved first guess (Grachev and Fairall, 1997).
6. The latent heat flux has been reformulated in terms of mixing ratio instead of water vapor density to eliminate the need for a Webb correction.
7. The gustiness velocity definition must be expanded to include the effects of mesoscale variability associated with convective precipitation using the approach of Redelsberger et al. (1999).

Two figures are shown to summarize the FASTEX flux analysis and indicate comparisons with the bulk algorithm.





The left panel shows the wind stress as a function of 10-m neutral wind speed and the right panel shows the latent heat flux. In both graphs the red dots are direct covariance measurements, the blue line the new version of the COARE bulk algorithm and the green line the old version. Although FASTEX had some winds over 20 m/s, they did not pass the quality control criteria. For this particular dataset, the model changes have improved the results for stress but not for latent heat flux.

The KF model (Kepert et al. 1998) has been used to investigate various aspects of boundary-layer interaction under the influence of sea spray and to aid the development of a simple droplet parameterization suitable for use in numerical forecast models. As part of this effort, a new droplet evaporation parameterization was developed that accounts for feedback effects This parameterization has been used in coupled air-sea simulation of hurricane Opal; significant droplet effects were found (Bao et al. 1999)

IMPACT/APPLICATIONS

The bulk flux routine incorporates many innovations (gustiness, cool skin and warm layer effects, proper convective functions, rain heat and momentum flux, Webb effect, and a saturation Richardson number in unstable conventions); it is expected to become a community standard and should be incorporated into operational weather forecast models (e.g., the Navy's). The work done on sea spray is expected to improve forecasts of strong storms Working jointly with Jim Edson, experimental techniques to measure fluxes from ships were advanced considerably over the last 4 years. The systems developed will greatly improve air-sea flux information in future field programs.

TRANSITIONS

As discussed above, the new bulk algorithm and bulk Richardson number parameterization could be adopted in Navy operational forecast models. Our new flux measuring techniques have been applied to the gas exchange problem.

RELATED PROJECTS

"Toward a definitive determination of air-sea gas exchange", NOAA Climate and Global Change Program. This is an investigation of fluxes and flux parameterization methods for trace gases (e.g., carbon dioxide) exchange processes over the ocean.

"Shipboard measurements of cloud-radiative properties in the tropical western Pacific", Department of Energy ARM program, (DE-AI02-92ER61366). This is a study of cloud forcing of the oceanic surface energy budget.

"Environmental sensing", DoD Advance Sensor Application Program (P.ETL.2090). Investigation of air-sea interaction aspects of remote sensing of the sea surface.

"Mid-Oceanic Wintertime Surface Fluxes and Atmospheric Boundary Layer Structure: Relationship to Cyclone Development and Evolution", NSF. O. Persson, P.I.

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